Illustration of Proliferation Resistance Assessment Through the French Fuel Cycle

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Abstract

Proliferation Resistance has become an essential issue of public interest and more generally for the acceptance of nuclear energy systems. It is implemented everyday. And proliferation resistance features prominently in "requirements" of Generation IV and other international or national work on innovative nuclear energy system concepts ; and proliferation resistance is also an integral part of the requirements defined by the INPRO project launched by the International Atomic Energy Agency. Proliferation Resistance Assessment Methodologies are being developed in several places in the world, making best use of past and recent works. Proliferation resistance is achieved through a combination of technical features which are defined as "intrinsic" to the technology and institutional and other measures, including safeguards inspection, defined as "extrinsic" measures. Work is still on-going to design a comprehensive methodology which will account for all elements and provide an integrated assessment for the proliferation resistance of a given nuclear energy system (a nuclear energy system is comprising the reactor and the fuel cycle, and is encompassing the whole life cycle). Analogies with the well established and widely proven concept of defence in depth in safety are considered. However, work already performed is providing the basic lines of analysis, and the building blocks of the assessment of the proliferation resistance of a given nuclear energy system. Those building blocks include the "quality" of the nuclear material, the "attractiveness" of the facilities, the safeguards inspection, the export control regime or the localisation and size of the fuel cycle services and facilities. This paper is reviewing the most significant of those indicators, and illustrate their use against real life examples coming from the French nuclear fuel cycle industry.

I. INTRODUCTION

The beginning of the 21st century witnesses a renewal in the interest for nuclear energy. This interest comes from the realisation of the huge energy needs from developed countries and fast increase o energy demand from developing countries, the concern of providing this energy without harming the environment and with a strong limitation of CO_2 emission, and the search for a diversified energy mix as one of the answer to the security of supply. Nuclear energy has benefits on all this counts. Such recognised benefits is driving the effective use of current power plants and fuel cycle technologies as well as the research and development efforts towards new "generation IV" technologies. At the same time, Iraq, North Korea or Iran are under scrutiny and remind us of the risk of using nuclear science and technologies to develop weapons of mass destruction. Looking back to the Atoms for Peace expectations 50 years ago, it must be recognised that efforts towards achieving non-proliferation of nuclear weapons did bear fruit. That being said, in the 21st century the concern of proliferation remains and shall be continuously addressed.

Indeed, non proliferation is not forgotten in current nuclear industry operation and developments. Most players in the world do operate with due respect to non-proliferation commitments (safeguards, export control,

…). The International Atomic Energy Agency (IAEA) as well as other regional safeguards and verification organisations (EURATOM, ABACC, …) are applying effective controls on nuclear material to ensure that they are used as declared ; and the additional protocol gives the IAEA further rights to check against undeclared nuclear material and activities. For the future, development programs integrate "proliferation resistance" as one of the "top level requirement" expected from nuclear energy systems. A case in point is the Generation IV International Forum : proliferation resistance was one of the top level parameters used to assess nuclear energy concepts. INPRO, another international initiative launched under the auspices of the IAEA features proliferation resistance as an important parameter to assess nuclear energy system. In line with the importance of the subject and the interest in the nuclear industry as well as in the public at large, several studies and cooperative works have been launched to better define "proliferation resistance".

This paper will look into what has been developed in the field of Proliferation Resistance Assessment Methodology, and illustrate some of the items with current, real-life examples.

II. PROLIFERATION RESISTANCE: DEFINITION AND KEY CONCEPTS

Obviously, non proliferation and proliferation resistance are not new concerns. Proliferation resistance and how to assess it has also a long history: we can record the INFCE study, an international work conducted through the IAEA in the mid-70's; a more recent work is the TOPS study, conducted in 2000 / 2001. This work has been led by the US-NERAC and involved the participation of several international experts. The international TOPS task force[1] recommended to build upon the concepts of attributes and barriers used by the US-National Academy of Science to further develop the evaluation of proliferation resistance.

It is important, for technical as well as political reasons, to reach an international consensus on such a key issue. The IAEA convened a technical meeting in October 2002, aiming at defining the "fundamentals" of proliferation resistance. This technical meeting put together international experts (USA, Russia, France, IAEA,…) The result was up to the expectation, providing agreed definitions on proliferation resistance and its key concepts[2]. We will draw on this most recent consensus work to define proliferation resistance and its key concepts.

II.A. Proliferation Resistance and Nuclear Energy System

Further to the heightened threat of terrorist activities, the first step of defining proliferation resistance is to decide where to draw the line between what is usually intended by the word proliferation. Here it has been decided to keep the traditional definition: the State intending to design and manufacture or to acquire a nuclear weapon. This does not preclude the use of some of the "barriers" which will be described later to prevent other types of threats such as sub-national groups which may want to buy or to design and build a nuclear weapon, acts of terrorism targeting nuclear facilities or acts of terrorism using radioactive material (such as a Radioactive Dispersal Device, the so-called "dirty bomb").

The second step is the formulation of the definition of proliferation resistance. The agreed definition comes as follows : "Proliferation resistance is that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States in order to acquire nuclear weapons or other nuclear explosive devices".

This definition is completed by the means to achieve proliferation resistance, described as follows : "the degree of proliferation resistance results from a combination of , inter alia, technical design features, operational modalities, institutional arrangements and safeguards measures".

Physical Protection addresses different threats and can be complementary to Proliferation Resistance. Physical Protection provides a set of measures aimed at preventing and protecting against the risk of intrusion in a nuclear facility or of theft of nuclear material or of an act of sabotage or an attack against a facility by individuals or a terrorist group.

The definition of proliferation resistance include the expression "nuclear energy system". The analysis of proliferation resistance (and of other requirements such as sustainability or economics) shall cover the full fuel cycle: the nuclear energy system is therefore covering a reactor concept along with its fuel cycle as a whole, that is from uranium mines to final disposal of ultimate wastes. In addition, recognising that those systems shall operate for several decades, and recognising the need to consider from the beginning the end of their life, the nuclear energy system shall be analysed through its whole life cycle.

In terms of proliferation resistance, the industrial or technical object shall be considered within its institutional environment : non proliferation commitments, industrial organisation, geographical deployment of the components of the fuel cycle, the national, regional and international verification and safeguards regimes, the export control mechanisms, etc… It makes sense, in terms of proliferation resistance, to widen the definition of system to include the technical as well as the institutional elements. And it supports the second part of the above-mentioned definition which explicitly refers to "institutional arrangements and safeguards measures".

II.B. Intrinsic Features and Extrinsic Measures

The discussion above and the second part of the definition of proliferation resistance introduce what appears in most work on the subject : the concept of intrinsic features which are basically technical and "embedded" in the technology and the concept of extrinsic measures which are mainly non-technical but which actively participate to proliferation resistance. The fundamentals of proliferation resistance recognise and stress the need to combine both intrinsic features and extrinsic measures to achieve an effective and efficient proliferation resistant system. In order again to foster consensus, the following definition along with some illustration have been agreed during the IAEA organised technical meeting. The definition of intrinsic features and extrinsic measures are as follows :

"Intrinsic proliferation resistance features are those features that result from the technical design of nuclear energy systems, including those that facilitate implementation of extrinsic measures".

"Extrinsic proliferation resistance measures are those measures that result from States' decisions and undertakings related to nuclear energy systems".

We will offer some concrete examples in the next chapter, and we will make the link between those definitions, and the barriers which have been proposed in TOPS.

II.C. Defence in Depth : a Fundamental Principle

The proliferation resistance fundamentals are not only definitions. We wish here to introduce also two other "fundamental principles" which are of special interest for designers.

Looking for a robust system, using several components and "barriers", the analogy with safety comes to mind. The first concept to be applicable is "defence in depth", useful to designers as well as to evaluators. Indeed, defence in depth is recognised also as a "proliferation resistance fundamental" : "Proliferation Resistance could be enhanced when complementary and redundant features and measures provide defence in depth".

Making the link with the "barriers", it calls for an analysis of the strength and usefulness of the barriers to prevent diversion or undeclared production of nuclear material. It does not make redundancy a mandatory requirement, it suggests looking at synergies and making sure no avenue for proliferation is left open. A simple example of defence in depth with complementary intrinsic and extrinsic barriers can be the use of low enriched uranium, in a reactor whose core is closed for long cycles, in a country having ratified the NPT, and subject to IAEA safeguards as well as regional verifications, a typical situation in the European Union.

Another "proliferation resistance fundamental" of significance for designers and developers is : "Proliferation resistance will be enhanced when taken into account as early as possible in the design and development of a nuclear energy system."

It is certainly already the case, since proliferation resistance is one of the top level requirement for developing Generation IV reactors. It is already the case in current generation facilities too : a typical example is the integration of safeguards approaches and equipments as early as possible in the design of fuel cycle plants currently under extension or commissioning such as enrichment plants in Europe or reprocessing plant in Japan; an other example is the development in the 90's of a "safeguards in depth approach" for the AREVA MELOX fuel fabrication plant in France[3].

III. LINKING BARRIERS TO INTRINSIC FEATURES AND EXTRINSIC MEASURES

The definition provided above of intrinsic features and extrinsic measures are clear in their principle. They call however for examples and illustration to get a concrete grasp of what it is. TOPS and other works have explored the field of proliferation resistance and came up with barriers or attributes of proliferation resistance, that we will introduce below. We will relate those barriers to examples of intrinsic features and extrinsic measures. Obviously, those examples are only examples. They do not intend to provide a comprehensive list, and may or may not be relevant depending on the characteristics of each nuclear energy system. It has also to be kept in mind that, when designing a nuclear energy system, it is necessary to find the best compromise between all requirements (economics, safety, environment, waste management, sustainability, ….) once an acceptable "minimum" standard is achieved for each requirement.

III.A. The TOPS Barriers

TOPS define three categories of barriers :

- Material barriers : barriers pertaining to the nuclear material itself
- Technical barriers : barriers pertaining to the technology and the facility
- Institutional barriers : barriers which cover safeguards and other extrinsic measures

For each of these categories of barriers, TOPS propose a more detailed analysis. More precisely, the material barriers are specified as follows : Isotopic, Chemical, Radiological, Mass and bulk

The technical barriers are specified as follows : unattractiveness of the facility, facility access, detectability, skills and time

The institutional barriers are specified as follows : Safeguards, access security, location

While TOPS is a well-known work, one may use a different set of barriers within each category, or expand the set of barriers in each category, or organise the barriers in a different classification. We will use below some of the barriers as illustrative of the intrinsic features and extrinsic measures.

III.B. Intrinsic Features and Associated Barriers

Intrinsic features relate mainly to technical aspects. We will here breakdown into material, facility and the technical actions which may facilitate safeguards and verification. This categorisation is close to the TOPS categorisation and to the generic examples given in the IAEA "Proliferation Resistance Fundamentals" report.

III.B.1 Attractiveness of nuclear material

The first example is a technical feature that reduces the "attractiveness" of nuclear material for a nuclear weapons programme. It looks at how easy or how difficult it could be to use a given nuclear material produced or used in the fuel cycle to design and manufacture a weapon. This generic example of intrinsic features directly relates to the TOPS material barriers. For each material barrier, we can even further refine the analysis. Let's take the isotopic composition as an example :

The isotopic barrier relates to the difficulty of designing and manufacturing a weapon. Several aspects shall be taken into account : critical mass, degree of isotopic enrichment, spontaneous neutron generation, heat generation rate, radiation. As a concrete illustration of isotopic enrichment, HEU (Uranium enriched above 20%) is more attractive than LEU, and within LEU enrichment of 4% is less attractive than enrichment of 19,9%. It is to be noticed that, in terms of proliferation resistance, relative comparisons are meaningful : it is not only a matter of threshold (LEU good / HEU no good). Threshold are useful but when analysing two nuclear energy systems relative comparison and subsequent design actions can strengthen the proliferation resistance.

The chemical barrier relates to the time and difficulty to extract the weapon usable nuclear material : a MOX fuel assembly is less attractive than pure plutonium powder. The radiological barrier relates to the difficulty to access and handling the nuclear material. Nuclear material contained in spent fuel features a higher radiological barrier than LEU fresh fuel.

III.B.2 Attractiveness of a facility

The second example will focus on the facilities : it could be a feature that prevents or inhibits the diversion of nuclear material ; and/or a features that prevents or inhibits undeclared production.

The "mass and bulk" material barrier and the "facility unattractiveness" and "facility access" barriers directly relate to this generic example.

Regarding "mass and bulk", for instance the use of large fuel assemblies makes more difficult their diversion. The facility unattractiveness will characterise whether the facility can readily produce weapon usable material or need modification for this, and whether such modification is difficult (cost, time, impact on safety). Taking enrichment, the gaseous diffusion technology is more difficult to modify or misuse than centrifugation technology. Taking reactor technologies, core with small reactivity margin may be more robust towards irradiation of undeclared targets.

The facility access is more related to access to the nuclear material and diversion or concealment of undeclared production. Taking reactors, a LWR which has a core closed during an 18 month cycle is more robust than a reactor with on-line refuelling. In a fuel fabrication plant, a fully automated production line reduces the number of access points and makes such facility more robust.

III.B.3 Facilitating verification

A last example of intrinsic features which bridge the gap with extrinsic measures is technical features which facilitates verification. This generic example can be related to the "facility unattractiveness" and the "detectability" technical barriers.

Regarding facility unattractiveness, when a facility is difficult to modify, it makes it easier for the verification agency to notice (through regular Design Information Verification). Regarding detectability, a simple illustration is a nuclear energy system where nuclear material control and accounting (NMC&A) can be done on a timely manner and with accuracy.

III.C. Extrinsic Measures and Associated Barriers

TOPS report recognised the importance of safeguards and other institutional barriers but did not go into as much a detailed analysis as for intrinsic features. The IAEA technical meeting report offers more consideration on this matter.

III.C.1 Commitments and Treaties

The States' decision and undertaking begins with a commitment to non proliferation. The best illustration is for a State to have ratified the Non Proliferation Treaty. It can be also party to other regional treaties such as nuclear weapon free zone treaties.

III.C.2 Verifications and Controls

The more visible extrinsic or institutional measure is the implementation of a safeguards agreement. It is also highlighted in the TOPS institutional barriers. The IAEA is verifying the non diversion of declared nuclear material and, when an Additional Protocol is in force, is best equipped to verify the absence of undeclared nuclear material and activities. In terms of proliferation resistance, it is worth noting that there is here again a gradation between States having in force a facility safeguards agreement, States having a full scope safeguards agreement, and States having in addition an Additional Protocol. Further gradation could be made on the way those agreements are implemented and on the efforts made by a State to facilitate verification (including sometimes going beyond the strict letter of the agreement to offer more), and to make its nuclear program transparent.

When there is a regional agreement providing for control of nuclear material, such as EURATOM in Europe or ABACC in Latin America, these additional verification measures are to be taken into account. It is to note that the nuclear energy fuel cycle of all European Union countries are controlled by EURATOM, regardless of their Nuclear / Non Nuclear Weapon State status towards the NPT.

Another example of extrinsic measures is the export control mechanism. It plays a key role in the non proliferation regime. The Nuclear Supplier Group offers guidelines for export control. In addition bilateral agreements may stipulate conditions on use and retransfer, and most State have enacted relevant regulation.

III.C.3 Industrial and commercial

The examples above are extrinsic and institutional. There are in fact other examples of extrinsic measures which are less institutional by nature but which can play an important role. The location barrier suggested by TOPS is one of them. More broadly we can look at the industrial structure of a nuclear energy system: geographical location (including need, number and location of "sensitive" facilities), multi-national ownership; and we can look at the commercial market: security and/or diversity of supply, spent fuel management offers, ….. A State with a not too large nuclear power program has less reasons to have its own enrichment or reprocessing plant when it can buy competitively such enrichment services or spent fuel recycling services.

These less institutional examples are also extrinsic measures which can play a significant role to ensure the proliferation resistance of nuclear energy system.

IV. ILLUSTRATION OF PROLIFERATION RESISTANCE BARRIERS IN THE FRENCH NUCLEAR FUEL CYCLE

Having moved from the general concept of proliferation resistance to a more in-depth understanding, we wish now to give life to those "concepts" and "barriers" by illustrating some of them through the workings of an actual nuclear energy system. We will use for this purpose the French nuclear energy system.

IV.A. The French Nuclear Fuel Cycle

The French nuclear energy system has been developed from the early 60's. As of today it includes more than 50 PWR reactors operated by EDF; fuel cycle facilities operated by AREVA group companies including COGEMA : a conversion plant, an enrichment plant (Eurodif) , fuel fabrication plants, a reprocessing plant at La Hague and an industrial scale Mox fabrication plant (MELOX); the design and servicing of power reactors (Framatome-ANP, an AREVA group company); and research and development spearheaded by the CEA. France has extensive international relations, whether commercial or cooperation.

The French policy on spent fuel management is reprocessing and recycling, with the target to reach an equilibrium between the quantity of plutonium obtained from reprocessing and the quantity of plutonium recycled in the existing PWR reactors.

Directly related to the extrinsic part of proliferation resistance, France has ratified the NPT, has a voluntary safeguards agreement with the IAEA and has signed and ratified the Additional Protocol to its safeguards agreement. Being an European Union Member State, all the nuclear material in the facilities of the French nuclear energy system are under the safeguards of Euratom. France is a member of the Nuclear Suppliers Group (NSG) and applies European Union regulation reflecting NSG guidelines, in accordance with its national export control policy.

We will now take some significant barriers and illustrate them with proliferation resistance features and measures implemented in the French nuclear energy system.

IV.B. Illustrating Extrinsic Measures

We will begin with extrinsic measures others than safeguards, since those measures are of importance for effective proliferation resistance but have not yet the level of understanding gained by intrinsic / technical features and safeguards verification.

IV.B.1. Export control

Export control is a sometimes unpopular but a widely effective tool to prevent proliferation of nuclear weapon and ensure that nuclear material and technology are put to peaceful use. France has a comprehensive mechanism for export control.

France in particular follows closely the NSG guidelines that put very stringent conditions for the export of sensitive technologies, such as reprocessing or isotopic separation. Restrictions and conditions are applying to the exportation of goods subject to export control (whether List I or “trigger list” on actual nuclear equipment or List II of dual use equipment).

Since 1992, « full scope safeguards » has been requested for List I items of NSG (INFCIRC/254 Part I); a derogation can be granted for safety-related items provided the concerned facility is under IAEA safeguards. Regarding the list II of NSG (INFCIRC/254 Part II), exportations to a Non Nuclear Weapon State are prohibited when there is a concern of diversion to a military program or a fuel cycle activity performed in an un-safeguarded facility.

In the European Union, the legal instrument translating this multilateral export control system, is the European regulation **n°1334/2000 of 22 December 2000**. Under this regulation, an export license is compulsory for exportation towards non EU countries for dual-use goods listed in its appendix, with some further restrictions for export control within the EU for some items ; as far as nuclear material, equipment and technologies are concerned, the list is the same than the NSG list. In this framework, the exportation of material, equipment and technologies related to sensitive technologies such as reprocessing or enrichment are subject to a strict control. Taking the example of exportation of HEU and of plutonium recovered through reprocessing and recycling ,while the general principle is the free circulation within the European Union, an export license is required also for the transfer of fresh and irradiated HEU and of “separated plutonium” within the EU: this applies also to fresh MOX fuel. In addition, for exportation outside the EU, an individual export license must be granted on a case by case basis. It is indeed the highest level of control.

Bilateral agreements can further specify the conditions for transfers, or can record authorised transfers. For instance, the France-Japan nuclear cooperation agreement of 1972 was amended in 1996 to record the transfer of technology from France to Japan for the Rokkasho-mura Reprocessing Plant. The France-Japan nuclear cooperation agreement and its amendments are published in the French Official Journal.

The French procedure to grant export licence is taking into account the sensitivity of exports related to reprocessing or enrichment. Granted by the Customs Department within the Ministry of economy, finance and industry (MINEFI) the authorisation of exportation can be given only after inter-ministerial consultation. When reviewing the application, the involved administrations take into account the NSG guidelines and France international commitments, as well as its nuclear export control policy. Complementary to the full-scope safeguards requirement, the decision is taken with due regard to the compliance of non-proliferation commitment of the receiving country, the implementation of physical protection at the adequate level, the legal international undertakings such as Conventions managed through the IAEA (Convention on Physical Protection, Convention on Nuclear Safety – 1996, Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management –1997), the internal situation of the receiving country, the compatibility of the exported equipment with the nuclear program and the technical and economical capabilities, or the safety of transport (transport conditions, inspection upon arrival…).

In addition to export control, France has also agreed to report export of nuclear equipment to the IAEA, as provided for in the Additional Protocol.

IV.B.2 Industrial organisation, serving a worldwide market

As mentioned above, in terms of extrinsic measures, the number and location of facilities, especially of fuel cycle facilities appear as one of the barrier. Other approaches such as multi-national ownership are also expected to be effective proliferation resistance barriers. These barriers are mentioned in several studies. We will discuss here two aspects : the number of fuel cycle facilities, and the concept of “multi-national” control or ownership.

The acknowledged more sensitive facilities in the fuel cycle are the enrichment facilities and the reprocessing facilities. An enrichment plant or a reprocessing plant is a highly capitalistic investment. Conversely, they can serve a large number of power reactors. This technico-economical barrier translates into an extrinsic barrier : there are few such plants. The size of the French nuclear program warranted the investment in France of an enrichment plant and of a reprocessing plant. The technology being mastered and the up-front investment being large, it was sensible for France to offer the same services to the export market. The proliferation resistance value of such an industrial choice is high : making such services available, a country with a nuclear power program of small to medium size can operate without building in its own territory an enrichment plant or a reprocessing plant. Today, Eurodif supplies around 100 Nuclear Power Plants in the world. La Hague services also around 100 Nuclear Power Plants in the world and return only fabricated MOX fuel assemblies; under French law France returns also final waste after conditioning to its customers.

Providing reprocessing services has also another proliferation resistance value : spent fuel is removed from the country, reducing concern of misuse in the short term and the more long term risk of a “plutonium mine” accumulated in spent fuel (who can predict what a country will be in 50 years?).

Technology transfer remains of course available under the export control rules previously mentioned.

Multi-national control is also a reality in the French nuclear industry. The first control comes from the fact that what is provided is a service : the nuclear material remains the property of the customer (the utility). EURODIF or COGEMA or fuel fabricator FBFC are therefore accountable to their customers. It is true in France, it is true also in other European Union reprocessing, enrichment, or other fuel fabrication facilities. The nuclear material being valuable, the customer is rightly expecting an accurate accounting. This proliferation resistance barrier is effective.

Now, multi-national control is more often related to ownership or financial control. Here again, it is a reality in the French fuel cycle : Eurodif's ownership include shareholders from Belgium or Spain (ownership however does not grant an automatic right to the technology nor to the industrial and commercial operation) ; the UP3 reprocessing plant was built and then operated for 10 years under a "cost + fee" contract associated to a capacity reservation.. While reactor design is considered less sensitive than enrichment or reprocessing, we can still mention that Framatome-ANP, being the merger of a French company and of a German company, is 34% owned by the private German company Siemens.

Widening the concept of multinational ownership or multinational control, apart from EDF and CEA, all other French organisations involved in the nuclear industry have the legal status of a private company. They are publishing regularly their accounts, are duly audited, are striving for transparency.

We are not arguing here that such model provides the strongest proliferation resistance barrier. We wish only to illustrate the concept of such possible barriers with actual examples.

IV.B.3 Commercial offer : a competitive and reliable supplier

Another extrinsic measures often cited is the commercial contracts and agreements to supply front-end services, possibly tied up with back end services. The preceding section gives insights on the economical and industrial rationale of such an approach.

At the government level, bilateral agreements provide a certain level of assurance, for instance by requesting authorisation from the supplier country to proceed to some fuel cycle activities such as enrichment beyond 20% or reprocessing. There are certainly cases where a bilateral governmental level agreement should request a "spent fuel take back policy".

Now, in most cases, a country or a customer will not feel secure if it is tied up to one supplier for a lifetime and has no choice. This is especially true for front-end services, but is also true for spent fuel management. That may drive such a state towards developing its own fuel cycle facilities for the sake of security of supply : it would then run counter to the goal of proliferation resistance.

The existence of a worldwide liberalised and free market is an insurance for security of supply and it has a proliferation resistance value. Providing that there is a sufficient number of suppliers, it ensures to nuclear operators a fair supply at a competitive price, and it makes therefore un-necessary (and uneconomical) the development of an indigenous capacity (unless the country is developing a large nuclear power program). This is especially true for sensitive technologies.

The French nuclear industry, and specifically the French fuel cycle services nuclear industry is in a position to offer each product or service of the front-end and of the back-end. And when a customer would request it, it can structure those services in a package covering front-end or back-end or both. Legal and financing modalities are to be adapted to these contract types. We trust that ensuring a free and open market is also a contribution to proliferation resistance.

IV.C. Illustrating Intrinsic Features

We will only briefly illustrate some intrinsic features, since intrinsic features are covered in more details in several works (US-NAS studies, TOPS report,…). We will take here only the example of the "attractiveness of nuclear material" and illustrate it with the case of plutonium management.

The nuclear material is the most obvious and the most central part of a nuclear weapon development. For this reason it is the focus of attention and the first object of safeguards and verification. It is all the most true for what is called by the IAEA "Unirradiated Direct Use (UDU) material" : a nuclear material which could be used to design and manufacture a nuclear weapon. Plutonium is such an UDU material. On a technical point of view, the physical and the chemical form may require further steps for direct use (need to go to a metallic form).

However, in IAEA safeguards terms plutonium is one category of UDU and no distinction is made depending of the characteristics of the plutonium (isotopic composition or physical / chemical form). In terms of Physical Protection, plutonium of any kind is warranted the highest level of protection, and in France the related provisions are strictly implemented.

Plutonium is or will be produced in basically all the reactor concepts ; recycling is a reality of today and most promising concepts for the future include recycling. In terms of proliferation resistance, the characteristics of plutonium can therefore be a useful discriminative factor when assessing and/or comparing the proliferation resistance of nuclear energy systems.

Plutonium of any "quality" may theoretically be used for manufacturing a weapon, but more or less easily depending on its quality. Analysing the isotopic characteristics of plutonium along the lines suggested in the TOPS barriers report (degree of fissile material, spontaneous neutron generation, heat generation rate, radiation), experts can classify plutonium in three categories : well-suited, possible but difficult, very difficult : choose another option.

The so-called "weapon grade plutonium" falls in the category "well-suited". The so-called "reactor grade plutonium" encompasses a large range of isotopic composition and would fit either in "possible but difficult" or "very difficult : choose another option".

The French nuclear fuel cycle policy is first to progressively increase burn-up in its reactors (LWR). In terms of proliferation resistance, the drawback on increased enrichment is negligible – at around 4.5%, it remains well below the 20% limit – but the advantages in plutonium characteristics is significant : a higher burn-up means a more difficult use for a nuclear weapon. The average burn-up of EDF fuels has increased from 33 GWd/t 10 years ago to 40-45 GWd/t today and is expected to further rise up to an average of around 55 GWd/t in the coming decade. For reference, the isotopic composition of plutonium in a 40-45 GWd/t LWR spent fuel contains around 25% of Pu240.

The other major French policy is to reprocess and recycle. In addition to the benefit in terms of waste management, it allows to reduce the overall inventory of plutonium. As mentioned above, destroying plutonium is better for proliferation resistance than keeping it in a final disposal, even if it is mixed with other radio-nuclides (which radioactivity will decrease with time). The first target is to reach an equilibrium between the quantity of plutonium obtained from reprocessing and the quantity of plutonium recycled in the existing PWR reactors. While current generation of PWR reactors are currently limited to 1/3 core of MOX fuel, the next generation of PWR reactors, the Framatome-ANP designed EPR, will be able to accept a 100% core of MOX fuel, allowing an increased burning of plutonium. One of the proliferation resistance advantage of reprocessing with recycling is therefore to reduce the overall inventory of plutonium. As mentioned above, this benefit is also offered to foreign customers.

Incidentally recycling plutonium in PWR further degrades the plutonium characteristics : the isotopic composition of plutonium contained in an MOX spent fuel is "worse" than for a LEU spent fuel : it is an additional proliferation resistance benefit.

We have considered here only the nuclear material attractiveness, the subject of this section. Proliferation resistance of a nuclear energy system is a matter of trade-off between sometimes conflicting aspects. The related reprocessing facility is certainly "attractive". Now, the combination of an attractive facility with relatively low attractive material being processed, international safeguards applied, only few such reprocessing plants which can serve a worldwide market, and the benefit of reduced plutonium inventory deserve consideration, even with today reprocessing technology. Further technological developments[4] such as pyro-reprocessing could further strengthen the proliferation resistance benefits of recycling.

V. CONCLUSION

Proliferation resistance is not an abstract concept. Technical or intrinsic measures as well as institutional and extrinsic measures provide concrete and effective barriers. Proliferation resistance barriers are already implemented in nuclear energy systems operating today, and they will be continuously deployed and possibly strengthened in the nuclear energy systems (reactors, associated fuel cycle, safeguards and verifications, export control, security of supply, ….) which are designed for the near future and the more distant future. This paper introduced barriers and gave illustration through real life examples, borrowing on the existing comprehensive French fuel cycle. What remains a challenge is to assess the strength and robustness of the combination of those barriers. Assessing the value of each barrier for a given component of the fuel cycle is a first step, integrating the value of one barrier for the whole fuel cycle from cradle to grave is more difficult, integrating the value of all barriers and find the best compromise between sometimes conflicting indicators is even more difficult. Work is currently under way in several countries to develop a Proliferation Resistance Assessment Methodology, or a set of methodologies. An international consensus is emerging on the key concepts of proliferation resistance, we expect that international cooperation will allow an emerging consensus on the Proliferation Resistance Assessment Methodologies.

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